

Main Author

Julie Williams-Byrd, Senior Systems Analyst, NASA Langley Research Center, Hampton, Virginia, USA, julie.a.williams-byrd@nasa.gov

Co-Authors

Jeff Antol, Aerospace Engineer, NASA Langley Research Center, Hampton, Virginia, USA, Jeffery.antol-1@nasagov
Sharon Jefferies, Aerospace Engineer, NASA Langley Research Center, Hampton, Virginia, USA,

Sharon.a.jefferies@nasa.gov

Kandyce Goodliff, Aerospace Engineer, NASA Langley Research Center, Hampton, Virginia, USA,
Kandyce.e.goodliff@nasa.gov

Phillip Williams, Aerospace Engineer, NASA Langley Research Center, Hampton, Virginia, USA,
Phillip.a.williams@nasa.gov

Rob Ambrose, NASA Johnson Space Flight Center, Houston, Texas, USA, Robert.o.ambrose@nasa.gov

Andre Sylvester, NASA Johnson Space Flight Center, Houston, Texas, USA, Andre.j.sylvester@nasa.gov

Molly Anderson, NASA Johnson Space Flight Center, Houston, Texas, USA, Molly.s.anderson@nasa.gov

Craig Dinsmore, NASA Johnson Space Flight Center, Houston, Texas, USA, Craig.e.dinsmore@nasa.gov

Stephen Hoffman, NASA Johnson Space Flight Center, Houston, Texas, USA, Stephen.j.hoffman@nasa.gov

James Lawrence, NASA Johnson Space Flight Center, Houston, Texas, USA, James.t.lawrence@nasa.gov

Marc Seibert, NASA Kennedy Space Flight Center, Orlando, Florida, USA, Marc.a.seibert@nasa.gov

Jim Schier, NASA Headquarters, Washington, D.C., USA, James.schier-1@nasa.gov

Jeremy Frank, NASA Ames Research Center, Mountain View, California, USA, Jeremy.d.frank@nasa.gov

Leslie Alexander, NASA Marshall Space Flight Center, Huntsville, Alabama, USA, Leslie.alexander-1@nasa.gov

Gary Ruff, NASA Glenn Research Center, Cleveland, Ohio, USA, Gary.a.ruff@nasa.gov

Jim Soeder, NASA Glenn Research Center, Cleveland, Ohio, USA, James.f.soeder@nasa.gov

Joseph Guinn, Jet Propulsion Laboratory, Pasadena, California, USA, Joseph.r.guinn@nasa.gov

Matthew Stafford, NASA Langley Research Center, Hampton, Virginia, USA, Matthew.a.stafford@nasa.gov

Abstract: NASA is transforming human spaceflight. The Agency is shifting from an exploration-based program with human activities in low Earth orbit (LEO) and targeted robotic missions in deep space to a more sustainable and integrated pioneering approach. However, pioneering space involves daunting technical challenges of transportation, maintaining health, and enabling crew productivity for long durations in remote, hostile, and alien environments. Subject matter experts from NASA's Human Exploration and Operations Mission Directorate (HEOMD) are currently studying a human exploration campaign that involves deployment of assets for planetary exploration. This study, called the Evolvable Mars Campaign (EMC) study, explores options with solar electric propulsion as a central component of the transportation architecture. This particular in-space transportation option often results in long duration transit to destinations. The EMC study is also investigating deployed human rated systems like landers, habitats, rovers, power systems and ISRU system to the surface of Mars, which also will involve long dormant periods when these systems are staged on the surface. In order to enable the EMC architecture, campaign and element design leads along with system and capability development experts from HEOMD's System Maturation Team (SMT) have identified additional capabilities, systems and operation modes that will sustain these systems especially during these dormant phases of the mission. Dormancy is defined by the absence of crew and relative inactivity of the systems. For EMC missions, dormant periods could range from several months to several years. Two aspects of uncrewed dormant operations are considered herein: (1) the vehicle systems that are placed in a dormant state and (2) the autonomous vehicle systems and robotic capabilities that monitor, maintain, and repair the vehicle and systems. This paper describes the mission stages of dormancy operations, phases of dormant operations, and critical system capabilities that are needed for dormant operations. This paper will compare dormancy operations of past robotic missions to identify lessons that can be applied to planned human exploration missions. Finally, this paper will also identify future work and analysis planned to assess system performance metrics and integrated system operations.

BACKGROUND

Journey to Mars

NASA is on a Journey to Mars (J2M), seeking to expand human presence into the solar system in a sustainable way. This strategy implements the policies outlined in the 2010 NASA Authorization Act and U.S. National Space Policy.

NASA's goal is not just to reach a destination, but rather it is to develop the capacity for people to work and learn and operate and live safely beyond the Earth for extended periods of time, ultimately in ways that are more sustainable and even indefinite. And in fulfilling this task, we will not only extend humanity's reach in space -- we will strengthen America's leadership here on Earth. To realize this goal, NASA is actively developing the capabilities that will enable humans to thrive beyond Earth for extended periods of time, leading to a sustainable presence in space. Investments in initial capabilities will be continuously leveraged and reused on the journey to Mars, enabling more complex operations over time. NASA's approach to pioneering is designed around a set of key strategic principles that will increase successes and rewards over the coming decades. These key principles for a sustainable, affordable space program provide overarching guidance to help ensure NASA's investments efficiently and effectively achieve the nation's goals.

As part of NASA's continuing efforts in space exploration, the agency regularly seeks to improve upon potential approaches for sending humans into deep space. The Evolvable Mars Campaign (EMC) builds on the results of other previous NASA studies focused on human exploration beyond low-Earth orbit (LEO), but instead of a point solution, the EMC employs a conceptual design philosophy that focuses on iterative trade analyses that embrace previous and parallel studies as well as new capabilities and technologies, new scientific understanding, and all interested and viable partnerships. The EMC trade studies are working toward a more optimal set of systems. The range and diversity of the trades are key and customer focused. The EMC was developed with an emphasis on programmatic flexibility, limiting unique capability development as much as possible, emphasizing modularity, progressively building to Mars surface missions, and slowing the cadence of missions to maintain affordability. The EMC represents a fundamental philosophy change to enable sustained human deep space exploration and results in a long-

duration presence on Mars, rather than optimizing for specific consecutive missions.

The EMC study is an ongoing series of architectural trade analyses that defines the capabilities and elements needed for a sustainable human presence on the surface of Mars. The Human Exploration and Operations Mission Directorate (HEOMD) leads the analysis, with subject matter expert participation across nine NASA centers and close coordination with other architectural analysis groups within the following organizations, the Science and Space Technology Mission Directorates and the Offices of the Chief Scientist and the Chief Technologist. The EMC identifies a set of operational capabilities and architectural trades required to sustainably expand human presence from LEO into deep space. The capability-driven EMC integrates science missions, robotic precursors, system maturation and risk reduction pathfinders, and a sustainable cadence of cargo and crewed missions that lead to an extended human presence on the surface of Mars. Several scenarios have been considered for a human mission to the Martian surface. Of these, only one spans all Mars vicinity destinations. The "Mars vicinity and Phobos, followed by a mission to Mars surface" scenario represents an ambitious campaign that leverages most of the capabilities and potential tradeoffs described in the EMC. This particular campaign acts as a point of comparison for future trade assessments and serves as the baseline reference campaign for the EMC. This baseline reference scenario is then used to evaluate capabilities, schedules, risks, challenges, and mitigation strategies.

EMC DORMANCY OPERATIONS

The EMC has defined several periods during the mission campaign when assets will be deployed to the Mars surface. There will be long periods of time between deployment of the assets and use when the astronauts arrive on the surface. Once the astronauts leave the surface of Mars, there will be additional long periods of time when assets will be in dormant stages then as well. It is critically important for the EMC to design elements and systems that will be monitored, repaired and survive during these dormant phases. Deployment of assets for human planetary exploration (e.g., a habitat on a planetary surface, a propellant module in orbit) may necessitate the maintenance of those assets in a dormant state for a period of time during transit, after deployment, and prior to arrival of the mission crews in order to preserve vehicle systems and associated consumables. The dormant period could range from several months to several years. Two aspects of uncrewed dormant operations are considered

herein: (1) the vehicle systems that are placed in a dormant state and (2) the autonomous vehicle systems and robotic capabilities that monitor, maintain, and repair the vehicle and systems.

Dormancy is addressed by the mission stage:

- During aggregation
- During transit to destination
- In orbit at destination, including:
 - Elements in orbit prior to deployment to surface or use by crew
 - Transit habitat while crew is on the surface
- On the surface of destination
- During transit in the return to Earth/Cis-Lunar vicinity

Dormancy operation needs also may change between periods of crew residency: (1) during the deployment phase, prior to crew arrival, or (2) between occupied phases, following departure of a crew and in preparation for arrival of the next crew. Each of these phases has unique requirements for establishing a dormant state and awakening from that state. See Figure 1

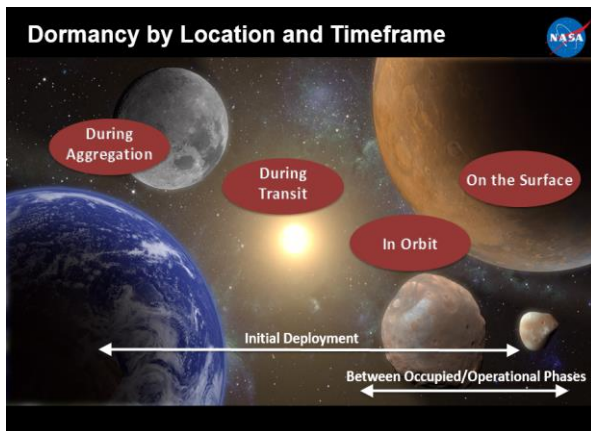


Figure 1. Dormancy Scope

Dormant operations are assumed for the following EMC elements:

- Transportation systems (Trans Earth Injection-Distant Retrograde Orbit Insertion (TEI-DROI), Trans-Mars Injection (TMI), Mars Orbit Insertion (MOI) stages) – while the overall vehicle may be active and operating autonomously during cruise, specific on-board systems such as primary propulsion may be dormant for long periods of time.

- Crewed elements (e.g., initial cis-lunar habitation, transit habitation, Phobos surface habitat, Mars surface habitat, pressurized rovers) – dormant during transit and after deployment (active following deployment for functional testing) and partially dormant between crew visits.
- Landers – descent stage landers are dormant during cruise, and after landing will supply their cargo (e.g., surface habitat) with the necessary resources, such as power to maintain a dormant state until the landers can be attached to the surface power source; landers with an ascent stage are dormant during cruise, while in orbit, and after deployment on the surface until needed by a crew for ascent to orbit. Onboard power and thermal systems are active for cryogenic fluid management to negate boil off of methane propellant. Once surface power is connected in-situ resource utilization (ISRU) systems can be activated for liquid oxygen (LOX) production.
- Support systems (ISRU unit, kilo-power unit, communications) – dormant during cruise but active on the surface after deployment, however, ISRU may have periods of dormancy between crew visits. ISRU remains onboard the descent stage to produce the LOX for the Mars ascent vehicle (MAV). The cryogenic fluid management (CFM) system goes with the MAV.
- Payloads (science instruments, prototype equipment such as ISRU) – dormant during cruise but active in orbit or on the surface after deployment. Some instruments require crew for operation, which may involve long dormant periods.

As stated previously, dormant periods could range from several months to several years. Table 1 provides anticipated dormancy durations of the EMC elements defined above.

Table 1. EMC Assumed Dormancy Durations

EMC Element	During Cis-lunar Aggregation	During Cruise to Destination	In Orbit at Destination	On the Surface of Destination	Return	Phase
Initial Cis-lunar habitat		1 yr				Deployment phase
			270-300 days			Between occupied phases
Phobos Surface Habitat		1 yr (to cis-lunar) & 3.3 yrs (to Phobos)	2 yr	1 yr		Deployment phase
				3 yr		Between occupied phases
TEL-DROI Stage		3.3 yrs (to Mars)	3 yr		1 yr (return to Earth)	Deployment phase
						Between occupied phases
TMI Stage	1.5-2 yr	1 yr				Deployment phase
						Between occupied phases
MOI Stage	1.5-2 yr	1 yr				Deployment phase
						Between occupied phases
Mars Taxi	0.5-1 yr	1 yr	1-1.5 yr			Deployment phase
						Between occupied phases
Transit Habitat	0.5 yr	1 yr (to Mars)	1-1.5 yr		2-3 yr (return to DRO)	Deployment phase
		1 yr (to Mars)			2-3 yr (return to DRO)	Between occupied phases
Mars Lander Descent Stage - Cargo only		3.3 yr		TBD		Deployment phase
						Between occupied phases
Mars Lander Descent Stage - Crew only		3.3 yr	1 yr	TBD		Deployment phase
						Between occupied phases
Mars Lander Ascent Stage		3.3 yr		1-2 yr		Deployment phase
						Between occupied phases
Mars Surface Habitat		3.3 yr		1 yr		Deployment phase
				4 yr		Between occupied phases
ISRU Unit		3.3 yr		1-2 yr		Deployment phase
						Between occupied phases
Kilo-Power Unit		3.3 yr				Deployment phase
						Between occupied phases
Small Pressurized Rover		3.3 yr		1 yr		Deployment phase
				4 yr		Between occupied phases

DORMANCY SYSTEM OPERATIONS

The types of general mission operations activities performed during dormant periods are a subset of those performed during the portion of the mission during which crew is present. Since crew is not present, these mission operations activities must be performed remotely, autonomously, or robotically. Mission operations includes:

1. System monitoring. The sensing technologies needed for monitoring critical systems and the environment (e.g., toxicity levels, pressurization for habitable modules; fluid state for tanks) to determine the vehicle operational condition and determine if timeline is being respected (see below). A critical aspect of this capability is determining how much and what data should be sent to the ground for analysis.
2. Execute timeline. Dormant operations will still require planning and performing activities, both during cruise and at the destination. Classes of activities on the timeline include:

- a. Maneuvers - Orbit and trajectory management, surface operations, perhaps rendezvous and docking. These activities are needed for thermal control, power management, and enabling communications.
- b. Logistics - Site preparation, resource production control and transport.
- c. Maintenance - Conducting periodic servicing operations to keep a system at a certain state of functionality during dormancy which will allow it to become fully operational when needed.
- d. Repair - Replacing failing or failed components or to restore malfunctioning systems will be needed to keep the vehicle in operational readiness.

The execution of the timeline can be distributed between vehicle system automation, robotic systems, and ground. This distribution will require analysis of tasks to determine suitability, analysis of robotic system and computational resources, etc.

3. Operational or occupancy preparations / departure preparations. Preparing systems for the dormant period post-departure by performing operations such as: stowing of equipment, flushing & purging fluid systems, and powering down systems to be maintained on keep alive power. Similarly, preparing the system for occupancy by bringing the cabin environment to a habitable temperature and air mix.

PAST ROBOTIC MISSIONS UTILIZING DORMANT OPERATIONS

Existing capabilities for dormant operations are primarily those employed by robotic planetary spacecraft such as New Horizons, Rosetta, and Dawn, from which valuable lessons can be applied to crewed vehicles since minimal experience exists in their dormant operation. Dormancy operation is common in long-duration robotic missions. For these types of missions, typically dormant operations may involve thrusters and associated plumbing being turned off until they are used, e.g., post-cruise, instruments are turned off until they are used. Other examples of this type of operation include dormancy employed for short durations during the Skylab program and an assessment of a “decrowed” mode for the ISS. The following sections provide brief overviews of these capabilities. New or different capabilities are needed for

human missions. Human missions use systems that are complex, which means sensors with increased performance may be used. Human mission systems are much larger than robotic systems and there are human systems like ECLSS that most robotic spacecraft don't have or need.

Human Spaceflight Missions

- Skylab - America's first space station was placed in a dormant state for several weeks between the Skylab 2 and 3 missions and between the Skylab 3 and 4 missions as well as following Skylab 4, which was the final crew visit to the station. A number of general lessons can be gained from the Skylab experiences. For example, while one flight controller described activation of the vehicle following a dormant state between crew visits as "only a little more complicated than when you come back from vacation," the crews found the job considerably more involved. Every job took more time than anticipated and a number of mistakes also slowed the activation. For example, an hour was lost when one of the crew on Skylab 4 left a valve in the wrong position while flushing the potable water system with iodine solution prior to opening a new water tank, and dumped the disinfectant into the waste tank. Frequent communications from Mission Control also caused interruptions that slowed operations during activation. Shutting down the vehicle and packing equipment to be returned also was a large job. Prior to the end of the Skylab 4 mission, Mission Control transmitted a list of changes to the deactivation and reentry checklists, which amounted to 15 meters of teleprinter paper being generated onboard Skylab.
- International Space Station (ISS) – ISS operated in a dormant/unscrewed mode for a year before the first crew arrived in November of 2000. Prior to this, ISS buildup flights took place from 1998 and 1999. While the ISS has not been placed in a dormant state during its operational lifetime, an assessment was conducted to define the capabilities needed to prepare the ISS in the event it would need to be "decrewed" and placed in an autonomous/dormant mode. The following desired capabilities were defined by the assessment. Preventative or corrective maintenance must be performed to address system degradation. Critical systems were

identified that needed to be redundant. For instance one half of critical loads in the U.S. Lab and Node 3 would have a jumper to a redundant cooling loop to prevent complete loss in the event of cooling loop leak. Maintaining visiting vehicle dock/undock and ground control and robotic capability was identified. In order to prevent loss of science it was determined that the ISS office and payload community had to work together to identify required activities to prevent loss of science. One other aspect of this assessment included atmosphere management pressure, temperature and humidity. The assessment showed the need to continue intra- and inter- module ventilation, in order to maintain U.S. orbital segment (USOS) atmosphere within temperature and humidity limits, was critical for the "decrewed" mode. Maintaining atmosphere management is critical for any human exploration mission that will undergo a dormant period. Atmosphere management is a critical capability for Mars surface systems especially deployed habitats and pressurized rovers. In order to minimize interruptions to services, maintenance and upgrades made prior to decrewed operation were also identified as critical capabilities.

Additionally, capabilities, such as a wireless leak detection system currently being tested on ISS that can quickly detect and localize leaks based on ultrasonic sensor array signals, potentially could be employed during dormant EMC operations.

Before viewing the critical systems and capabilities needed for dormancy operations, this next section will describe notional Mars surface operations. The Human Spaceflight Architecture Team (HAT) Mars Destination Operations team developed this notional mission. Information in this section will detail the specific operations needed including dormancy operations and will assist with linking operations with needed critical systems and capabilities identified in the next section.

NOTIONAL SURFACE MISSION CONCEPT OF OPERATIONS

A notional end-to-end Mars mission was defined in a 2013 study (HAT Mars Destination Operations Team FY2013 Final Report, 7 Nov 2013), which included six mission phases to help define the operations functions and capabilities needed for surface systems:

- Phase 0 – Prior to Cargo Landing
- Phase 1 – Post Cargo Landing (~2-4 Years)
- Phase 2 – Crew Landing & Acclimation (~7-30 Sols)
- Phase 3 – Local Exploration (~30 Sols)
- Phase 4 – Regional Exploration (~230-410 Sols)
- Phase 5 – Preparation for Ascent (~30 Sols)
- Phase 6 – Post Crew Departure

An overview of the mission is presented here, highlighting specific aspects related to dormancy. During the in-space transportation phases, there is an extended period of time (~3 years for the DRA 5.0 case up to ~7 years for the EMC cases) between the launch of surface system assets until all of these assets are put into use after the crew arrives. Typically, the first lander in all examples will carry the fission surface power system (FSPS) and a deployment system to off-load and move the components of this system to its operational location – approximately 1000 meters from the lander. This will be an activity that occurs at the beginning of Phase 1. The crew's MAV will land with the FSPS or on the second lander and must be connected to the FSPS in order for ISRU system to begin making LOX for ascent. One or two small robotic rovers will be part of the cargo delivered during Phase 1 and will be operated by personnel on Earth throughout the remainder of Phase 1. Surface assets other than the FSPS, ISRU plant, and small surface rovers will remain dormant until the end of Phase 1. The first cargo lander for the second (and subsequent) crew will carry the MAV and a fresh ISRU plant. This ISRU plant must be connected to the FSPS. Note that in all of these examples this cargo lander will arrive while the first crew is still on the surface and that crew will insure that the power system is connected (this is likely to be the case for all subsequent crews although not all trajectory opportunities have been examined to substantiate this). All other landers (and the surface assets they carry) will remain dormant until the arrival of the next crew.

In all examples there is a period of time, ranging in duration from about 8-9 months for the Mars DRA 5.0 study case to about 3-4 years for the EMC cases, when no crew will be present. During this time, the MAV for the next crew will be actively making LOX, which implies that the FSPS and ISRU plant will be fully active. Robotic rovers will resume the remotely operated type of activity that occurred during Phase 1 of Mission 1. All other surface systems are likely to be dormant for the duration of Phase 1. The crew habitat could be problematic in this phase because of potential difficulties placing the environmental control and life support systems (ECLSS)

into a dormant state once this system has been wetted.

During Phases 2 through 5, all surface assets are assumed to be operating some or all of the time. The ISRU plant will be operating but at a reduced level to provide any make-up LOX needed by the MAV or to produce breathing gases for extravehicular activity (EVA) and habitation make-up. The FSPS will be operating at nearly full power while the crew is at the primary habitat. Traverses using the two small pressurized rovers will be a common event during Phase 4. These traverses are assumed to last for two weeks. During these traverses the main habitat is occupied by 2 crew members and therefore is not put into a dormant mode, allowing for any-time return of the crew. When not on a traverse the small pressurized rovers are likely to remain in operation to provide habitable space for the crew as well as to allow maintenance, restocking, etc. The small robotic rovers are assumed to be continuously operating during Phases 2-5 either under the control of the surface crew or personnel on Earth. There are two small unpressurized rovers available for the crew to be used in the general vicinity of the landers, assisting local EVAs. These rovers are also assumed to be part of a contingency rescue system while the small pressurized rovers are on a traverse. Thus these rovers will be very active during Phases 3 and 5 and will be on stand-by during the traverses conducted in Phase 4. Science instruments are assumed to be active periodically during Phases 2-5 but the duty cycle is difficult to project. Some of these instruments will also remain active during Phase 6. A “large” drill is one exception to this comment about science instruments. This device is likely to be used only under the supervision of the crew, but for planetary protection reasons the crew will likely tele-operate this device. It is likely to be used several times only during Phase 4 of the surface mission and otherwise remain dormant.

DORMANT OPERATIONS OF HUMAN SPACECRAFT SYSTEMS

The previous section described notional Mars surface operations. This section will describe specific capabilities and systems that have been identified by SMT subject matter experts. Initially, planned operations during dormant periods were defined and assessed at a system level in order to define the unique capabilities which will be needed by each vehicle system. The information presented here was derived from representative operations of individual systems of the surface habitat during dormant periods.

Vehicle Systems Operated During Dormant Periods

Communications and navigation supports the transfer of information between in-space elements and from in-space elements to the ground, as well as tracking those elements to determine orbits and trajectory maneuvers.

Long-range communications and navigation will remain active during periods of dormancy, since a state of awareness will be needed for receiving commands and providing telemetry to ensure that the dormant vehicle systems are nominally reporting their state to the ground and if teleoperations are planned. Point-to-point and short range comm systems may be inactive at times, but will be needed to support rendezvous and docking operations with an approaching vehicle as well as monitoring of ascent/descent operations and surface operations. An important mode for the communications and navigation system during dormant periods will be fault management, if it experiences a problem it may need to take appropriate autonomous action.

The environmental control and life support systems and environment monitoring (ECLSS-EM) provides essential life support and monitoring capabilities for the crew.

Dormant operations will require unique ECLSS capabilities for: monitoring, maintenance, safing operations, and surface operations. Expanded monitoring of the pressure and atmosphere will be needed to detect structural leakage, potentially caused by micrometeoroids & orbital debris (MMOD) or leakage of the systems into the cabin. The levels, pressures, etc. of stored fluids & consumables also will need to be monitored. If fans and ventilation motors are required to maintain thermal conditioning during dormant periods, parameters such as the motor power vs speed, pressure drop, etc. will need to be monitored to detect failures. The periodic measurement of fluid quality may also be needed but is less frequent. Additional types or locations of sample points of environmental monitoring will need to be addressed. With the expanded monitoring capabilities and the extended operational lifetimes, sensor life and calibration is a concern, with the potential need for autonomous recalibration of sensors and definition of associated calibration standards. The data resulting from the monitoring will need to be periodically analyzed to determine the effects of dormancy on ECLSS functions such as

oxygen generation, waste water recovery, fluid quality, etc.

Preventative maintenance tasks will need to be conducted during dormant periods and may include: periodic exercising of moving components (fans, cycle valves); recirculation to filter/flush stored fluids; microbial control of surfaces or parts (ultraviolet (UV) light, vapors in air); and maintenance of different environmental conditions than during crewed operations (i.e., lower than usual temperatures, different atmospheric pressures or gas mixtures) to reduce microbial growth or extend life of ECLSS components. Stored consumables also would have residual biocides to prevent microbial growth. Corrective maintenance tasks also may be needed during dormant periods, and would include the dosing of biocide or flushes after “failed” measurements. The proper mix of on-orbit data analysis to identify issues or trigger maintenance versus examination of patterns or trends in the measurements from Earth will need to be determined.

When a crew prepares to depart a vehicle, safing operations will need to be conducted to place the ECLSS in a dormant state and prepare it for use by the next crew. For example fluid systems will need to be flushed with clean or other appropriately treated fluids. Safing operations will require additional consumables for the flushing/purging operations, the activities may be time consuming for the crew, and the operations will present additional challenges when conducted in microgravity. When the next crew arrives following a dormant period, the ECLSS will need to be reactivated, the system performance will have to be evaluated prior to crew arrival, and the environmental conditions assessed before crew entry into the vehicle.

ECLSS systems used in surface habitats will have additional challenges, including the need to interact with the ISRU system to recharge fluid stores. If a reduced oxygen (O₂) atmosphere is employed during dormant periods (as discussed in the fire safety section), excess nitrogen also may be required from the ISRU. Additionally, an in-situ sterilization capability may be needed to address planetary protection concerns.

Fire safety is considered a branch of ECLSS.

Dormant operations will require unique fire safety capabilities in the areas of monitoring, fire suppression, fire cleanup, and occupancy preparations. Continuous monitoring of system states will be needed that could indicate short circuit/smoldering as well as periodic air circulation and monitoring of the cabin atmosphere. The current fire suppression systems typically are hand-held and employed by crew members. The lack of crew during dormant operations will drive the need for a fixed suppression system, which in previous spacecraft have been mass prohibitive. An option would be to employ a robotic system with the ability to use an existing hand-held gaseous (not water based) suppression system or a robotic “Synchronized Position Hold Engage and Reorient Experimental Satellite” (SPHERES) with sensing and fire suppression capabilities. In the event of a fire, an automated cleanup system would be needed to remove the gaseous combustion products from the atmosphere. Another concern for fire detection and suppression arises if a reduced O₂ atmosphere is used during a dormant period. The timeframe for restoration of the cabin to a habitable atmosphere (21% O₂ at 1 atm. of pressure) will need to be defined if it occurs in days, weeks, or months in advance of the crew arrival. In this timeframe, as the system transitions between a reduced O₂ atmosphere and a habitable atmosphere, the best approach for fire detection and suppression also will need to be defined.

The power system generates and manages the power necessary to operate the vehicle.

The power system will need to be active at all times during dormant operations and most likely would not be shut down in order to maintain propellant conditioning and keep the avionics and communications systems operational and the heaters active to maintain system temperatures. However, if a reduced power mode is used during dormancy there would be no need to shunt power for solar powered elements; the array regulator will continue to regulate the voltage and the excess power will be radiated off the back of the array. In the event of a complete shutdown due to some type of catastrophic failure, the system should include a “Lazarus Mode” to allow the power system to be restarted and will include a long life emergency battery that would enable an emergency restart in the

event that all else fails. Additionally, the kilowatt power unit, batteries, and solar arrays may require maintenance during dormant periods: charge and discharge cycles and the depth of the discharge will impact the battery life and capacity, while the radiation environment in Mars orbit will degrade the solar array performance. Active dust mitigation will be needed on the solar arrays.

Propulsion provides crew and cargo transportation from the Earth’s surface, through space, to an exploration destination, and back. Five key capability areas include: (1) high-thrust, in-space propulsion; (2) low-thrust, in-space propulsion; (3) descent propulsion; (4) ascent propulsion; and (5) attitude control propulsion.

Dormant operations will require unique propulsion capabilities for system monitoring, propellant storage & transfer, and long duration environmental exposure. Propulsion systems will require monitoring during dormant periods to assure that pressurant leakage, propellant leakage, and propellant boil-off (with goal of zero boil-off under steady state operations) is within acceptable low levels. As with other systems, an approach also will be needed for health monitoring and checking of the main propulsion system prior to reactivation following a dormant period.

First-of-a-kind, long-duration cryogenic propellant storage and transfer systems will be needed for terrestrial and in-space use during dormancy, incorporating cryogenic fluid management technologies:

- Propellant quantity monitoring and gauging (in gravity and in microgravity)
- Very long-duration low-leakage cryogenic valves and regulators (requires development)
- Passive propellant conditioning systems (including low-conductivity structures, advanced multi-layer insulation, thermodynamic vent systems with propellant acquisition, and vapor cooled shielding)
- Active propellant conditioning systems for boil-off control incorporating new cryocoolers

Zero-G propellant acquisition and propellant conditioning/delivery will be needed for the attitude control system (O₂/methane (CH₄)),

which is also used for minimizing solar heating and for station-keeping. On the surface, automated propellant transfer associated with ISRU production will be needed.

A number of concerns and challenges exist related to long duration environmental exposure of propulsion system components during periods of dormancy. The reliability of electrical components such as engine igniters, controllers, thrust vector control (TVC) motors, avionics, batteries in electromechanical actuators (EMAs) are a concern after long duration exposure to radiation. Degradation of materials over long duration space and Mars surface environment exposure is another challenge. For example, valves sticking or leaking due to degradation of seals will drive valve technology development and redundancy strategy. Degradation of lubricants for moving parts, TVC, etc. also is a concern. Composite overwrapped pressure vessels (COPVs) could experience overwrap failures due to radiation exposure as well as stress rupture failure modes due to pressure cycles and thermal cycles. Additionally, the potential for foreign object debris (FOD) may drive design to all metal tanks. MMOD and surface debris have the potential to affect multiple systems. The integrity of tank and propellant line insulation must be maintained since it is difficult to repair. As the vehicle life requirement is extended system robustness must be considered. (Current references such as vacuum jacketed tanks and lines with multilayer insulation (MLI) provide a passive option albeit with a potential mass penalty). Long durations also have the potential for an increase in helium demand for purges, pneumatics, and possibly for engine restart requirements.

Structures provides the mechanical support for the vehicle systems and consists of two main capability areas: (1) Primary structure and (2) secondary structure.

Dormant operations will require unique structures capabilities for system monitoring, modeling, and self-healing materials. Autonomous sustainment of habitat and vehicle structures in the in-space and planetary surface environment will be a reliability challenge, both through extended periods of occupancy and dormancy. Since data currently are not available on long term exposure of crewed vehicle spacecraft structures in a deep space

environment (from either environmental material/structural aging or discrete source damage threats such as MMOD impacts), continuous health monitoring (diagnosis & prognosis) and evaluation of structural integrity, residual strength, and life of critical elements will be needed. This monitoring capability will include integrated vehicle health monitoring (IVHM) (e.g., microphones, strain gauges, and embedded sensors) along with non-destructive evaluation (NDE) capabilities (e.g., ultrasound, thermography, x-ray,). IVHM will need to be operational and continuously collecting data prior to integration and launch and throughout all mission stages as well as supporting diagnostic or prognostic data. Using certified physics-based models, informed by the real-time IVHM data to adjust the structural and system integrity (life), the resulting data will be analyzed by mission controllers who will decide to adapt mission parameters to ensure safety or to recommend repair and maintenance operations. Certification of the structures following dormant periods in the in-space/surface environment also will be needed. Additionally, use of autonomous self-healing/failsafe materials incorporated into the habitat primary structures can aid prevention of atmosphere leakage due to an impact event. A robotic capability potentially could be used to conduct structural inspection operations (e.g., NDE) and perform associated preventative & corrective maintenance activities during unoccupied periods.

Thermal provides thermal control for spacecraft, management of cryogenics, and protection from the heat of atmospheric entry, ensuring spacecraft and crewmembers are maintained within safe and comfortable limits. It includes three key capability areas: (1) active and passive thermal control, (2) thermal protection systems, and (3) cryogenic systems.

Dormant operations will require unique thermal capabilities for: monitoring and maintenance of spacecraft and surface element thermal control systems. Spacecraft system temperatures will require monitoring in order to control heat rejection turndown. Thermal transport loop fluid quantities will be monitored for leakage evaluation and cryogenic fluid quantities will be monitored to assess boil-off rates. Thermal transport loop pump performance will be monitored as well as thermal transport loop fluid

chemistry for corrosion evaluation. Preventative maintenance capabilities during dormant periods include dosing of the thermal transport loop for correct chemistry maintenance. Corrective maintenance may include the need for remote valve control for radiator loop isolation to compensate for potential leaks. The capability to swap transport loop pumps through an automated transition may also be needed. Surface element thermal systems will require capabilities for monitoring radiator surface emissivity to assure radiators maintain an appropriate heat rejection capability during dormant periods. Periodic removal of surface dust from the radiators will be needed to maintain the appropriate heat rejection capability, which could be accomplished through automated capabilities such as coatings or an electrostatic cleaning system to repel dust particles. Additionally, a robotic system to periodically clean dust from radiator surfaces could be employed.

Autonomous and Robotic Support Systems

The following sections discuss those capabilities provided by the autonomous and robotic systems to support the overall vehicle and supporting subsystems during dormancy:

Autonomous mission operations (AMO) includes all protocols, controls, and systems to ensure missions are executed safely and effectively, and includes four capability areas, which vary based on whether mission control (ground), crew, or systems within the vehicle are performing the function: (1) monitor displays, (2) perform procedures, (3) execute timeline, and (4) fault management:

Dormant operations will require unique AMO capabilities in all of the above defined capability areas. Monitoring displays will not be performed on the vehicle during dormant periods since no crew are present. However, system displays in mission control (ground) will need to be managed similar to how deep space (Mars and outer planets) robotic missions are conducted today. As the time delay increases, real-time monitoring on the ground becomes more batch-driven data playback and analysis.

Pre-planned initiation of procedures will be conducted on-board the spacecraft to operate vehicle systems as part of a plan uplinked from the ground (see execute timeline below). These

procedures can be part of maintenance activities, science activities, maneuvers, etc. Procedure execution status will be recorded and sent to the ground for analysis (e.g., when the procedure started, ended, succeeded or not, steps/commands performed). Procedures must be flexible enough that, in case there are unexpected events or faults, the vehicle does not have to immediately halt procedure execution, but can proceed by postponing or promoting steps, reordering steps, or skipping steps that are overtaken by events. Once the vehicle reaches distances of larger than ~1 light minute, initiation of procedures and direct commanding from the ground becomes inefficient for nominal operations. However, in some cases, initiation of procedures from ground can be performed even at Mars distances.

Execute timeline is the automated execution of the plan as uplinked from ground. The plan includes the procedures to perform, as discussed above; the difference is that the plan consists of sequences of procedures, including multiple procedures active simultaneously. As with the procedures, the plan should also be flexible enough that, in case there are unexpected events or faults, the vehicle does not have to halt plan execution immediately, but can proceed by postponing or promoting activities, reordering activities, skipping activities that are overtaken by events, and opportunistically performing activities if time permits. Significant problems (major faults or inability to replan due to difficult constraints) will be reported to ground, and addressed in the ground-based planning cycle (see fault management below). The daily, weekly and monthly planning of spacecraft activities will be similar to the process currently utilized for spacecraft, including analysis of resources (power, ECLSS, mass properties, trajectory and navigation). The daily plan will be uplinked to the vehicle and activity status will be returned from the vehicle to the ground in a manner similar to that currently used for Mars and outer-planet robotic missions. Note this may mean that, on a specific day, the status from yesterday's plan is available, while today's plan is being executed, and tomorrow's plan is being produced.

Fault management or IVHM onboard the vehicle will require the ability to detect, isolate and

recover from time-critical faults. On-board fault management may change a plan (see execute timeline above) to perform fault-specific procedures (see Procedures above). If the fault cannot be identified, recovered from, or mitigated, then it must be managed on the ground. As distance increases, the number of time critical faults increases as well. The onboard fault management function must generalize existing onboard fault-management functions to address more problems than traditionally managed onboard low Earth orbit (LEO) spacecraft, due to the larger time delays between ground and spacecraft. In the presence of complex faults or non-time-critical faults, the ground will conduct analysis of faults, planning fault recovery actions, and pre-planned initiation of procedures to operate vehicle systems to recover from faults as part of a plan (see execute timeline above). Some ground-based commanding to retrieve high-rate data for analysis is possible even at Mars distances.

Robotic systems enable dormant operations by performing preventative and corrective maintenance tasks that human crews typically would perform during occupied phases. EMC robotic systems can be divided into two archetypes based on the mobility approach and where the system is used (intra-vehicular activity (IVA) or EVA).

Dormant operations will require incorporation of robotics capabilities into crewed and uncrewed spacecraft to perform preventative and corrective maintenance of human serviceable spacecraft systems. The use of robotic systems for maintenance and repair of spacecraft systems during dormant periods is analogous to human tended facilities in a terrestrial environment. The robotic system requirements for these types of tasks will vary according to the maintenance and repair requirements of the spacecraft systems. These spacecraft systems will be designed to allow servicing, repair, or replacement of components up to entire subsystems. Archetypes of robotic system requirements to conduct maintenance and repair of this type include lightweight, dexterous and strong hands that are able to handle interfaces like handles, knobs, valves, and power tools. Lightweight and strong arms will be able to position tools, connect cables and hoses, and carry spare parts to a worksite. Mobility for micro gravity is more akin to

climbing, so robotic legs and feet are designed to interface with crew hand rails and other hard points on spacecraft designed for human use to provide access to maintenance and repair sites. On the outside of spacecraft there will be specialized interfaces for EVA gear like the worksite interface fixture, a socket designed to receive stabilizing foot restraints used by the human crew. Today's robots are able to handle tools and objects as previously described, and board-level maintenance on computers, replacing valves, cleaning tubes and filters, swapping fuses, and other small scale maintenance is possible. All systems need to have design requirements that accommodate these robotic maintenance and repair capabilities.

Robotics will conduct monitoring tasks, such as inspecting plumbing and electrical networks by using instruments and hand sensors. Troubleshooting & board level diagnostics and repair also will need to be conducted by robotics, as appropriate. Prior to maneuvers, robotics may conduct inspections to identify loose hardware "floaters" and ensure they are secured. Similarly, robotics can play a role in logistics tasks by locating and returning objects to inventory, using radio-frequency identification (RFID) readers and vision systems. Robotics also will be needed to perform a number of preventative maintenance tasks, identified as being serviceable by robotics, such as: maintenance of orbital replacement unit (ORU) elements; inspecting and cleaning tubes and filters; and cleaning touch surfaces to prevent biofilm and other biological growth. Likewise, robotics will perform corrective maintenance tasks such as: removing computer boards and installing new ones; replacing valves and tubes; and replacing wear components like tires, blankets and covers on surface systems. Robotics also will be used on the surface for tasks in preparation for occupancy/ departure, such as: unloading cargo from landers/logistics supply vehicles; collecting geological samples; setting up large scale science instruments like geophones; loading of science payloads for return to earth; and inspection, safing, & shutdown of systems as needed.

Several additional candidate robotic capabilities needed to support dormant operations also were identified in the vehicle capability section:

- Robotic capability to use existing hand-held gaseous fire suppression system
- Robotic capability such as SPHERES with sensing and fire suppression capabilities
- Robotic capability to conduct structural inspection operations (e.g., NDE) and perform associated preventative/corrective maintenance activities
- Robotic capability to periodically clean dust from radiator surfaces on planetary surface

In addition to AMO and robotics, ISRU also will support surface systems during dormant periods as well as require capabilities and support from AMO and robotics.

ISRU capability involves any hardware or operation that harnesses and utilizes in-situ resources to create products and services for robotic and human exploration. ISRU is composed of five capability areas: (1) resource characterization and mapping, (2) mission consumable production, (3) civil engineering and surface construction, (4) in-situ energy generation, storage, and transfer, and (5) in-situ manufacturing and repair.

In preparation for dormant operations, ISRU may support occupancy and departure tasks by providing resources for safing operations. From a Mars ISRU perspective, there are 4 potential purge gases that can be used for safing operations: carbon dioxide (CO₂), nitrogen (N₂), argon (Ar), and hydrogen (H₂). For cryogenic systems, only H₂ has a low enough melting point to prevent freezing of liquid O₂ and CH₄ areas. However, N₂ can be used for purging ‘warmer’ areas, such as dormant engines, but can’t be used to purge lines after usage. ISRU also may require support from robotic systems to perform preventative and corrective maintenance to ISRU systems, including rovers, during dormant periods.

An overview of the unique capabilities needed for the individual spacecraft systems during dormant operations of long-duration human exploration missions was presented in the individual system sections above.

SUMMARY

This paper has identified critical operations needed to survive dormant periods identified in the EMC. Also, key capabilities needed for a variety of systems have been identified and analyzed. This information will assist the continued study of the EMC and can be used for future human exploration mission trade analysis.

Summary of key drivers during dormancy operations:

- Expanded sensing and monitoring capabilities will be needed beyond what is currently employed on existing vehicles, such as ISS.
 - Additional sensors throughout vehicle and systems
 - Sensor life and calibration is a concern
 - Multiple vehicles may be dormant at one time that will need to be monitored
 - Impacts to on-board and ground communications/data systems
- The execution of dormant operations will need to be balanced between vehicle system automation, robotic systems, and ground control.
 - On-board software to detect faults, determine the root cause, determine the ramifications of the root cause, and define appropriate course of action
 - What level of on-board processing will be required versus downlink to ground?
 - Robotics capabilities needed to perform preventative and corrective maintenance
- Preparations for dormant periods between the operational/occupied phases will present unique challenges.
 - Reactivation activities to bring the vehicle out of a dormant state
 - Capabilities/operations to place vehicle in dormant state after being operational

FUTURE WORK

The HEOMD’s EMC and SMT activities will continue to study dormant operations applicable to human exploration of Mars. The next phase of analysis will include identification of performance metrics where applicable

and the dependencies of systems that would enable successful dormant operations.

ACRONYMS

Acronym	
ACS	Attitude Control System
AMO	Autonomous Mission Operations
Ar	Argon
AR&D	Automated Rendezvous and Docking
atm	Atmosphere
ATV	Automated Transfer Vehicle
CH ₄	Methane
CO ₂	Carbon Dioxide
Comm/Nav	Communication and Navigation
COPV	Composite Overwrapped Pressure Vessels
ECLSS-EM	Environmental Control and Life Support Systems and Environment Monitoring
EMA	electromechanical actuator
EMC	Evolvable Mars Campaign
EVA	Extra Vehicular Activity
FOD	Foreign Object Debris
FSPS	Fission Surface Power System
H ₂	Hydrogen
HD	High Definition
ISRU	In-Situ Resource Utilization
ISS	International Space Station
IVA	Intra-Vehicular Activity
IVHM	Integrated Vehicle Health Monitoring
LAN	Local Area Network
LEO	Low Earth Orbit
LOX	Liquid Oxygen
MAV	Mars ascent vehicle
MBSU	Main Bus Switching Unit
MLI	Multilayer Insulation
MMOD	Micro-Meteoroids & Orbital Debris
MOI	Mars Orbit Insertion
N ₂	Nitrogen
NASA	National Aeronautics and Space Administration
NEO	Near Earth Objects
NDE	Non-Destructive Evaluation
O ₂	Oxygen

Acronym	
ORU	Orbital Replacement Unit
PAN	Personal Area Network
PCS	Portable Computer System
RCS	Reaction Control System
RFID	Radio Frequency Identification
SM	Russian Segment Service Module
SPHERES	Synchronized Position Hold Engage and Reorient Experimental Satellite
SSI	Solar System Internet
TBD	To be determined
TEI-DROI	Trans Earth Injection-Distant Retrograde Orbit Insertion
TMI	Trans-Mars Injection
TVC	thrust vector control
USOS	U.S. Orbital Segment
UV	Ultraviolet
WAN	Wide Area Network

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